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Caribbean storm surge mapping – an overview towards guidelines

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Hurricane waves and surges can have a crippling effect on economic growth in Caribbean island states. In reducing the vulnerability to these disasters, exposed areas to storm surge must first be identified and inundation levels predicted. Various methods and models have been applied to estimate storm surge at sub-regional scales and for coastal sites and towns. The approach used to filter and utilise the hurricane data, and the statistical methods employed to develop final values are often different. The territories through different funding agencies have sponsored several projects to map storm surge, but there has not been a single unified project or approach. This paper puts into perspective the requirements for storm surge evaluation, outlines the varying approaches relevant for the region and re-emphasises the need for an established set of regional guidelines.

Notation

$D_{\min}$	minimum distance from the eye of each storm to the location of interest
e	Euler's number (2·71828)
P_c	central pressure in the storm
$pV_{\max\_yr}$	peak $V_{\max}$ for a particular year
$R_{\max}$	radius to maximum winds in the storm
$V_{\max}$	maximum wind velocity
yr	particular year

1. Introduction

1.1 Objective

The Caribbean region is not currently guided by any set of definitive storm surge mapping procedures. In recognising the absence of regional guidelines, this paper is intended to aid with the development of an appropriate set of procedures and guiding principles for predicting and mapping storm surges in the Caribbean. The lack of regional guidelines affects a wide range of agencies and professions. This paper is intended to assist the following organisations.

- Those various funding agencies or government agencies, which manage storm surge hazard mapping projects for formulating relevant and applicable terms of reference (TORs) for these projects.
- Environmental regulatory agencies, who in reviewing development applications are faced with a plethora of different techniques for calculation of storm surge.
- Engineers and scientists, who when faced with very general TORs can assess which method would be the most applicable to specific situations and, in so doing, better address the needs of their clients.
- Town planners and disaster management agencies who, when faced with the challenges of town planning and evacuation planning, would require some assistance in determining methods best suited to their needs.

1.2 Background

The waves and surges generated by tropical cyclones within the North Atlantic Basin (hurricanes) have extremely damaging physical effects on both inland and coastal regions throughout the Caribbean. The long-term effects are often crippling to the economic growth of the small Caribbean island states. Over the past decade, these natural disasters in Latin America and the Caribbean have led to cumulative damage of approximately US$73 billion (Zapata and Madrigal, 2009). Of note was Hurricane Ivan in 2004, which resulted in an estimated US$595 million in damages and losses, with a computed impact of 8% of gross domestic product (GDP) (UN ECLAC, 2004). Hurricane waves and surges are a significant damage contributor in these events.

Climate change is likely to increase the frequency and intensity of hurricane activity in the region (Smith *et al.*, 2002). This means increased exposure to storm waves and surges. To minimise the risk of damage to property and loss of life, vulnerability to these events must be reduced through improvements to the physical and social infrastructure. Vulnerability reduction starts with an initial identification and continuous updating of the potential storm surge impact to coastal areas.

The prediction and mapping of storm surge is a multi-phase procedure. The critical phases, in not necessarily this order, are usually: (*a*) selecting and filtering the available data; (*b*) carrying out a statistical analysis on either the 'raw' data or estimated storm surge conditions; (*c*) developing representative conditions through statistical analysis; (*d*) calculating the storm surge values (typically through modelling); (*e*) estimating inundation levels and plotting these levels on to a map. Perhaps the two most critical aspects of the multi-phase storm surge procedure are the statistical analysis and the modelling of the storm surge.

1.3 Statistical methods

The framework of the statistical analysis is usually developed from one of or a combination of the following well-known and accepted methods.

- The peak value method (PVM) used for the list of actual historical occurrences, whereby the highest condition from each past storm is statistically analysed to work out the various return values.
- The annual maximum method (AMM) is similar to the PVM but the database of storms is filtered to use just the highest storm conditions for each year of the period of record. This method has traditionally been used in hydraulics for river flooding analysis.
- The joint probability method (JPM) whereby probability functions are developed for the individual parameters of the storms (maximum wind speed, forward speed, central pressure, etc.) under the assumption that these parameters are statistically independent of each other. Synthetic storm conditions are then generated from a combination of these probability functions.
- The design storm approach (DSA) whereby a particular category of storm is selected and the worst-case scenario of this storm modelled to provide an envelope of maximum conditions.
- The empirical simulation technique (EST) which uses a sampling of past storms to generate a larger database of synthetic future storms under the assumption that future events will be statistically similar in magnitude and frequency to past events.
- The Monte Carlo Method (MCM) which is similar to the EST but adjusts the statistical basis for the future synthetic hurricanes based on projected increases in frequency and intensity of storms that may or may not come about from climate change.

1.4 Storm surge modelling

Models are an important part of storm surge computation. The following models either have been applied or are relevant for application within the region.

- ADCIRC/SWAN, which has been used with a flexible mesh to model storm surge in the Caribbean basin (Dietrich *et al.*, 2011). Although giving useful results, the drawback to this model combination has been the requirement for large computing power.
- TAOS, which has been used primarily at a regional scale to provide storm surge estimates in the context of an envelope of maximum occurrences. For more local scales, the TAOS model appears to have some limitations.
- SLOSH, which is an older generation model that also required large computer generating power, operates on a curvilinear grid system and does not include wind-driven waves.
- MIKE 21, which can be used in either flexible mesh or rectangular grid modes, and combines the effects of waves and hydrodynamics.
- Delft 3D, which can be applied for the simulation of storm surge (Vatvani *et al.*, 2000, 2002). For modelling of waves, Delft 3D, is able to automatically link the tide and storm surge module to the open source SWAN model.

1.5 Approaches to storm surge and inundation mapping

Each of the statistical methods and models has pros and cons and each may be combined in a variety of ways to generate the storm surge and inundation values. The Caribbean territories, through different funding agencies, have sponsored many projects which have been carried out with diverse methods and techniques. For example, over 10 years ago the Caribbean Disaster Mitigation Project (CDMP) and the United States Agency for International Development (USAID) funded the HurAtlas project for the Caribbean which used the JPM and the TAOS model. Between 2009 and 2011, the Inter-American Development Bank and the World Bank funded two separate Natural Hazard Management projects for coastal towns in Jamaica which used the PVM in conjunction with the model MIKE 21.

The inconsistencies in the approaches adopted exist for various reasons. The most fundamental is probably that different professionals tend to use their preferred approach and model. However, oftentimes, other reasons have had a significant bearing on these decisions such as: (*a*) tailored approaches to suit inadequate budgets as the best or most appropriate models can be expensive; (*b*) lack of knowledge of the various statistical approaches; and (*c*) different sites are thought to require different techniques based on topography or bathymetry or other geographic characteristics.

Three methods of developing storm surge and inundation maps will be explored within this paper. In the first instance, the statistical method called the PVM will be applied to deep water wave conditions. These conditions are estimated from each past hurricane occurrence using a hurricane parametric model. An extremal analysis is then carried out on these conditions to determine the values for various return periods (for example 50, 100 and 150 years). Each return value is then transformed from deep water to the shoreline using a numerical computer model. The storm surge and inundation levels are determined from these results. This method requires computational time for just the wave conditions for the return periods of interest and thus can be easily carried out.

The second method uses a computer model to simulate conditions for each past hurricane thereby producing wave and storm surge conditions at the shoreline for each hurricane. The maximum surge values are then extracted and fitted to a statistical distribution (using the PVM approach) to determine the values for the various return periods. This method differs from the first one in that whereas the PVM was applied to the deep water wave conditions in method 1, here they are applied to the modelled storm surge values at the site. This method is computationally expensive as it requires computer simulation of all historical storms, but the results, provided that the model is calibrated, yield a better representation of the distribution of storm surge at the project site.

The third method uses the statistical approach called the MCM to develop a series of synthetic storm tracks. These tracks are developed based on the properties of the past hurricanes (as with the EST approach), but giving consideration to the potential for future increases in hurricane frequency and intensity. This method is intended to evaluate potential effects from climate change on hurricane activity. In this analysis, impacts under various 'worst-case' scenarios can be investigated and past hurricanes can be simulated with different tracks, forward speeds or intensities (similar to the DSA). This approach can be especially useful for disaster management agencies for evacuation plans and early warning systems.

It is hoped that within this paper, through the discussion and analysis of the various methods, that the benefits and the limits to the applicability of each method will be realised, towards the development of a set of guidelines for storm surge computation for the small island states of the Caribbean.

2. The inputs to storm surge estimation

2.1 The components of storm surge

Storm surge is defined as the elevated water level that accompanies hurricanes and which creates flooding and causes damage to coastal infrastructure. Storm surge has static components comprised of the inverse barometric rise (IBR), wind set-up and wave set-up which may occur over a period of several hours. The dynamic component is wave run-up which varies over shorter time intervals based on the period of the incident waves.

The pressure in the 'eye' of the hurricane compared with ambient atmospheric pressure elevates the water level beneath the hurricane; this is referred to as the IBR. The IBR is affected not only by the pressure differences but also by the distance to the storm. Therefore, the location of the hurricane eye relative to the project site at any point during the passage of the storm is crucial to IBR determination. Often, the point of highest IBR does not correspond to the time of maximum waves.

The wind set-up refers to the tilt in the water surface which occurs to balance the stress from the wind pushing the water onshore. The wind set-up is inversely proportional to the water depth at which the wind shear is occurring. The islands within the Caribbean Sea have relatively narrow continental shelves and so this is not as significant a component of storm surge as it may be elsewhere in the world. There are some areas, however, such as the south coast of Jamaica, the Grenadines and the sand banks around Turks and Caicos and the Bahamas that are more exposed to wind set-up because of a wider continental shelf.

Wave set-up refers to the increase in the mean sea level which balances the halting forward motion of wave energy as a wave breaks. This component is significantly affected by the near-shore bathymetry as the across-shore profile of the seabed affects how much, and where, wave breaking occurs. For example a shallow near-shore reef, such as the bank reefs throughout the Caribbean and fringing reefs around Barbados, will cause the waves to break and lose their energy but this in turn increases the wave set-up component of storm surge.

In the computation of the storm surge components, it is also necessary to consider the normal range of tidal fluctuations that occur. Because hurricanes are generally slow-moving systems, their storm surge effects may occur at any stage of the tide or during spring or neap tide. Consideration for the entire tidal range is therefore important. In several cases the worst-case scenario is desirous and so the highest astronomical tide (HAT) should be applied to the value of storm surge calculated.

Finally, the impact of long-term sea level rise should also be considered, as this will result in an increase in the elevation of the starting datum on which storm surge must be computed.

Elevated water levels due to the static surge can remain relatively constant for hours during a storm, whereas water levels in the wave run-up zone on sloping shorelines such as beaches will fluctuate as waves 'run-up' the beach profile and on to the land. All components of storm surge must be considered in any chosen methodology and should be represented by the storm surge predictions.

2.2 Data requirements

The data requirements and sources of all the data used for the computation and analysis of storm surge are listed in Table 1.

2.3 Historical hurricane activity

The accuracy of wave analysis methods depends largely on the accuracy of the available database of hurricane records. In the North Atlantic Basin there are relatively good records of hurricane activity linked to the high frequency of storm occurrences. The region is exposed to hurricane activity each year between June and November. Especially since the late 1960s, data logging of hurricane parameters has improved tremendously.

There are hurricane databases, such as that of the National Hurricane Center (NHC), which contain records of hurricane tracks and their main components, the central pressure and the maximum wind speed. Also available, but on a smaller scale, are recorded hurricane wind and wave conditions. These records are mostly in the form of point measurements from buoys that give the variation in time but not in space. Other remote sensing methods from aircraft flights and satellite imagery provide the spatial variation in the generated wave conditions. However, these data are generally only available for calibration and validation of a model as opposed to doing long-term analysis.

Ascertaining the historical hurricane activity in the vicinity of the areas of interest is the first step in all three methods that will be outlined herein. A thorough search should be made of an available database of tropical storms and hurricanes. All storms which passed within a specified radius of the project site (typically 300 to 400 km radius is usually satisfactory) should be extracted from the database. This will result in a list of storms, and storm parameters relevant to the project site which can then be utilised within the model.

2.3.1 Utilising historical data

Oftentimes, the historical database is not complete and approximations have to be made to compensate for missing data. For example, the central pressure and radius to maximum winds are two parameters essential for the estimation of hurricane wind field, and hence the wave conditions. However, these data are often not available.

The central pressure data for North Atlantic storms were not recorded until reconnaissance flights started in 1968. Prior to this, the data were not available but can be estimated through the use of the expression proposed by Banton (2002)

$$P_c = 1014 - \left(0{\cdot}029 \times V_{max}^{1{\cdot}626}\right)$$

where P_c is in millibars and V_{max} is in knots.

Another relation to central pressure, also developed by Banton (2002), is utilised to estimate the radius to maximum winds, namely

$$R_{max} = 3 \times 10^{-6} e^{0{\cdot}017 P_c}$$

where R_{max} is in km and P_c is in millibars.

Consideration needs to be given to the fact that storm tracks are typically provided at 6 h intervals. As such, depending on the speed of a storm, recorded points may be far away from a project site. Interpolation of the various storm characteristics between recorded points is therefore often necessary to capture the impacts of the storm when it is closest to the site of interest.

3. Storm surge modelling

3.1 Applicable models

There are many models used to compute storm surge; several which have been applied within the region are shortlisted in Section 1.3 above and their validations are discussed here.

Historical storm characteristics	NOAA's and NHC's hurricane database
Satellite imagery	High-resolution satellite imagery
Seabed	Existing bathymetric charts
	Bathymetric surveys completed at project sites
Beach profiles	Beach profiles completed at project sites
Topographic mapping	Topographic mapping from relevant survey departments
	Spot elevations taken within the project areas to append the topographic maps. In coastal areas with flat terrain, the existing topographic maps often do not carry sufficient detail
	Ideally LIDAR surveys or use of other remote sensing technologies should be explored

Table 1. Data used for storm surge calculation

- The unstructured-mesh SWAN spectral wave model and the ADCIRC shallow-water circulation model have been integrated into a tightly coupled SWAN+ADCIRC model. The resulting hurricane waves and storm surges from the coupled model are validated in the work of Dietrich *et al.* (2011) for Hurricanes Katrina and Rita. The coupled model has been shown to be highly capable and demonstrates the importance of inclusion of the wave-circulation interactions.
- In 1995, National Oceanic and Atmospheric Administration (NOAA) undertook a comparison of TAOS, SLOSH and a French storm surge model. In that work, NOAA concluded that all three produce 'reasonable' forecasts that are generally consistent with observations from actual storms.
- Storm surge hindcasting and forecasting has been simulated using MIKE 21 around the Irish Coast and the results have been verified through the work of Elsaesser *et al.* (2010). The hydrodynamic modelling capabilities of MIKE 21 have been similarly verified in Klein's work (Klein, 1998) which used two locations in Vanuatu as case studies. MIKE 21 has also be validated against measurements of storm surge inundation from Hurricane Ivan, 2004 in the flat coastal community of Portland Cottage (Smith Warner International, 2010)
- Delft 3D modelling results have been verified repeatedly, such as the work conducted in India and Vietnam by Gelfenbaum *et al.* (2007). The capability of Delft 3D to predict the storm surges associated with tropical cyclones as well as to produce a reliable estimate of the inundation has been demonstrated in these works.

3.2 Development of hurricane simulation models

In areas that have narrow continental shelves, such as the Caribbean, the total surge is smaller than elsewhere; but the relative contribution of wave effects to this total surge is generally greater. This underscores the important fact that whatever storm surge model is utilised in the Caribbean, it must include wave effects such as breaking. Models which feature a coupled mode, namely the ability to model the mutual interaction between waves and currents using a dynamic coupling between the hydrodynamic module and the spectral wave module, are the most applicable to the narrow continental shelves of the Caribbean.

3.2.1 Creating a computational mesh

All of the aforementioned models utilise the bathymetry and topography of the area in the form of a computational mesh. Models tend to use either finite-difference or finite-element, or both, grid systems. Entire Caribbean islands should be represented in the model domain, extending out to water depths greater than 1000 m, and extending more than 100 km from the coastline. Smaller mesh elements, or nested grids, should be used in the areas of interest to represent the bathymetry with higher resolution.

The computational meshes should be created from geo-referenced bathymetric charts, relevant topographic contours and satellite imagery, as well as the merged existing and surveyed bathymetric and topographic data. These components will define to the model in use, the land and seabed elevations. The computational mesh is used in the numerical transformation of the hurricane conditions to the near-shore areas and up on to land to allow for simulation of the dynamic surge (run-up) on to the shoreline.

3.2.2 Hurricane modelling

In addition to bathymetry and topography, necessary input to any hurricane model includes: time, maximum wind speed, radius to maximum wind speed, central pressure, ambient pressure and coordinate position (latitude and longitude). Where there is a lack of necessary data, estimations can be made as described previously. With this input, conditions can be computed at hourly intervals for each storm wave and water level as the hurricane is tracked along its path.

The accuracy of the model computations should be verified through field observations where available and/or subsequent inundation mapping for historical hurricanes. Calibrating the models in this manner dramatically increases the confidence in the results obtained.

4. Storm surge estimation methodology

Three methods of storm surge inundation mapping will be explored within this section.

4.1 Method 1: Deep water wave statistics

This method determines the storm surge effects of a hurricane based on storm wave parameters derived from the hurricane's motion over deep water. This approach saves on model computational time as each hurricane wind field is not numerically simulated over the model domain. A statistical analysis is first done on the deep water conditions and then the representative conditions for the various return periods are used as input into the numerical models.

The hurricane conditions can be determined using parametric models, some of which are simplified from complex numerical modelling. Parametric models estimate wave conditions from the main parameters of a hurricane such as the maximum wind speed, forward speed, central pressure and radius to maximum winds. Young and Burchell (1996) proposed one such model which was calibrated with more than 100 satellite measurements of hurricane wave heights. Other hurricane conditions such as the IBR may be parametrically determined using a similar parametric formulation, such as the one given in the *Shore Protection Manual* (USACE, 1984).

The steps involved are listed here.

(1) The hurricane conditions (waves and water levels) are determined at a deep water location offshore the site of interest. This may be done using a parametric model such as the one proposed by Young and Burchell (1996). The waves should be determined for different directional sectors.
(2) An extremal statistical assessment is carried out on the deep water wave conditions to determine various return periods (usually 25-year to 150-year). This statistical analysis may be carried out according to the proposed steps by Goda (1990).
(3) The conditions for the various return periods are inputted into a numerical model and waves are transformed from deep water up to the shoreline.
(4) Storm surge conditions at the site can then be determined for various return periods and direction of wave approach.
(5) Inundation lines can thereafter be overlaid onto satellite imagery for the project site, and then storm surge hazard maps can be prepared.

This is the quickest of all three methods outlined, in terms of computational time. The primary limitation with this approach is that the time-varying effect of each hurricane is not captured. In reality, the highest storm surge may not necessarily occur under the highest wave conditions. However, due to the relatively close proximity to deep water of most coastlines within the Caribbean, this method is still an applicable approach.

It should be noted that method 1 is likely to provide the highest values for storm surge because of the simplified approach used.

4.2 Method 2: simulating storm surge for historical hurricane events

This method uses a computer model to simulate conditions for every past hurricane, thereby producing wave and storm surge conditions at the shoreline for each. This approach is evidently quite thorough given that the time-varying conditions for each past hurricane can be evaluated. The following steps are involved.

(*a*) Using a coupled wave-hydrodynamic model, such as MIKE 21, all storms should be simulated. The storm parameters for each hurricane should be inputted into the model and the associated waves and water levels generated by the storm calculated in a time-varying manner. The near-shore conditions are then estimated as the storm moves along its track. For example, for the south coast of Jamaica, there have been over 100 storms which have passed within 300 km. From that number, the 30 or so with the highest wind speeds could be extracted and input into the numerical model; and for each hurricane the storm surge value at the site determined. In doing this, one might find that hurricanes with the highest wind speeds do not necessarily create the highest on-shore storm surges. A slow-moving category 3 storm could likely result in a higher storm surge than a category 4 storm with a greater forward speed.
(*b*) For each hurricane, the maximum computed storm surge value for the duration of the storm should be extracted from the model at three or more points along the project shorelines. The points should be chosen at locations a reasonable distance along the shoreline. In locations where there is a significant dynamic component of storm surge, a parametric formula should be used to calculate the dynamic run-up component which can then be added to the static storm surge values. It should be noted that because of the flat nature of some shorelines and lack of gently sloping land–shore interface, run-up may not be a major component when considering inundation.
(*c*) An extremal analysis should be carried out with these storm surge values from which various return period events can be identified. This statistical analysis may be carried out according to the proposed steps by Goda (1990) and the values for the various return periods determined.
(*d*) Based on the local topography, the extent of inundation can then be plotted and overlaid onto satellite imagery for the project site. Storm surge hazard maps can then be prepared in two possible ways: (i) based on the inundation levels determined for each return period; or (ii) by selecting from the list of storms modelled those which produced inundation levels close to each return period and using these as 'design' storms.

This method is a thorough approach but requires significant computation time and effort which is not always budgeted for or required based on the characteristics of the project site. For instance, on a relatively straight shoreline within close proximity to the continental shelf (1 to 5 km), method 1 may be just as suitable. However, for project sites and communities that are within bays with complex near-shore bathymetries, or areas with relatively wide continental shelves, this method is probably the most suitable.

4.3 Method 3: synthetic storms for climate change (Monte Carlo Method)

The fundamental basis of hindcast statistics is that past occurrences are representative of the future. However, proper disaster planning requires evaluation of 'new possibilities'. For example, the south coast of Jamaica, as far as historical records show, has never been impacted by a storm such as Hurricane Ivan (2004). Some degree of forecasting and speculating is thus useful in the planning process, especially in light of climate change concerns.

There is global scientific concern that climate change will result in more frequent and stronger hurricanes. Therefore a method of storm surge mapping should account for the potential impacts of climate change. The third method outlined herein attempts to do this by looking at the possible increases in intensity and frequency of hurricanes.

The Monte Carlo approach requires the generation of a synthetic database from the properties of the existing historical population. It is applicable only to situations where the main parameters of the parent population are regarded as statistically independent of each other. The randomness associated with hurricanes, along with the very weak correlation between the main parameters, makes this method very applicable. A Monte Carlo method, proposed by Smith *et al.* (2002) is described here.

(*a*) Some prediction should be made of the likely increase in peak V_{max} for the particular year (up to 100 years ahead) of interest for the project area. This prediction can be based on assumptions by the Intergovernmental Panel on Climate Change (IPCC) or on other scientific speculations such as the formula

$$pV_{\text{max\_yr}} = 0{\cdot}26(yr - 1900) + 60$$

derived by Smith *et al.* (2002).

(*b*) The historical hurricane database should be used in the determination of the peak V_{max} as well as the likely minimum distance to the location of interest for each storm (D_{min}).

(*c*) An appropriate distribution for the peak V_{max} and D_{min} should be determined and random values of both parameters from the distributions generated which should be equal to the number of synthetic storms required for the analysis.

(*d*) A storm track from the parent population should be selected at random.

(*e*) A random peak V_{max} should be assigned to the storm and adjusted so that the new D_{min} is one of the randomly generated values. The V_{max} at each point in the storm should be scaled by a constant, equal to the ratio of the real peak V_{max} to the random peak V_{max}.

(*f*) For example, Hurricane Donna which passed within 20 km of the British Virgin Islands with a maximum wind speed of 140 mph (225 km/h) might be selected at random. If the randomly selected D_{min} in this case was 60 km, then the entire storm track would be moved offshore away from the British Virgin Islands to this new D_{min}. Further if the maximum V_{max} selected at random is now 170 mph (274 km/h) for example, then Donna is assigned this new V_{max} at the same point it reached 140 mph and all other storm points along the track are scaled up to the same ratio.

(*g*) Each synthetic storm should be simulated in a numerical model with an initial water level condition of the predicted GSLR (global sea level rise) as per the preferred IPCC scenario predictions and the HAT of the predicted tidal range.

(*h*) The predicted inundation for each synthetic storm can then be statistically analysed as per method 2 and the values for the various return periods determined. The synthetic storm results should be combined with those for the real tracks and extremal analysis conducted. In so doing, the data set of storms increases and the 'time of record' also increases. The inundation zone can then be plotted and overlaid onto satellite imagery for the project site, and storm surge hazard maps prepared.

Method 3 investigates synthetic storms that could represent worst-case scenarios by varying various parameters of the past storms. It considers that a site can be impacted in the future by a more severe storm than has happened over the period of record. Further, where there has been an extreme storm that may be an outlier in a statistical distribution, this method helps to fill the gaps in the statistics to help to define the most appropriate statistical distribution function to develop the return values of storm surge.

Method 3 has two major benefits over the other methods.

- The first is that the synthetic storms incorporated in method 3 fill the gaps in the database between the storm population and the outliers, making for a more cohesive dataset.
- The second benefit is that where there are periods of relatively low hurricane activity, or no data for recent activity, method 3 creates an opportunity to provide a design storm. For example, the last hurricane to severely impact the island of Barbados was Hurricane Janet in 1955; and prior to Hurricane Ivan's impact on Grenada in 2004, that island had not been significantly impacted since 1980. Applying method 3 therefore allows for the consideration of possibilities that are just not on record as yet but ought to be included to provide a good statistical picture, particularly when considering long return periods.

4.4 Combination of methods

Hybrid methods developed from a combination of the proposed methods are also possible. For example, if the focus of mapping is on developing evacuation plans and early warning systems, then a joint approach that looks at storm surge from different hurricane categories with different tracks may be applied. This could involve the following steps.

(*a*) Simulate all hurricane tracks as per method 2 and develop the data set of storm surge values from each hurricane.
(*b*) Carry out the extremal statistical analysis to determine the various storm surge levels for different return periods.
(*c*) Associate storms from each hurricane category with the different return periods to develop an appreciation for a link between the storm category, track, and the level of inundation.
(*d*) Select a sample population of storms of interest based on this assessment.
(*e*) Apply the Monte Carlo approach of method 3, with the selected sample of storms, to vary the intensity and track of these storms. The Monte Carlo approach would allow the simulation of a range of possible tracks and intensities for each storm in the sample.
(*f*) Develop maps of maximum envelope of highest waters (MEOHW) for each category or track type.

4.5 Comparison and application of methods

The proposed methods outlined in the sections above provide a way to estimate then map storm surge hazards with both a medium and long-term outlook.

There are many of applications for these methods, but it is important to note that no single method is necessarily suitable for all applications. Consideration must be given to the physical characteristics of each site or coastal community being studied, available time for execution, available budget and the objectives of the project (for example, evacuation planning versus long-term disaster risk reduction).

The limitations for application of each of the approaches discussed have been summarised in Table 2.

The following may be concluded from analysis carried out.

(*a*) Method 1 is simple and has the shortest computational time but may be an overly conservative approach. It is also unlikely to be applicable for complex nearshore bathymetries.
(*b*) Method 2, once the model is validated and there are sufficient data points to provide a satisfactory statistical fit, is applicable to all cases unless the projected increase in storm occurrence due to climate change is to be included in the analysis.
(*c*) Method 3 allows long-term changes in hurricane frequency and intensity to be incorporated in the analysis and could be especially applicable in cases where there is an outlier storm, or for sites that have had a relatively quiet history of storm occurrence. It is however computationally the most expensive approach.
(*d*) Method 3 may be modified to develop synthetic storms for evacuation planning.
(*e*) As long as there are no guidelines, different methods will be used, leading to a disparity in the planning process across the region.

4.6 Discussion

As indicated in the sections above, each method has its limitations and its various applications. The storm surge estimation techniques are relevant to a fairly wide range of fields. Most notably, they are applied in a predicative capacity for use in disaster mitigation and town planning, both through the use of inundation maps.

4.6.1 Disaster mitigation

There have been debates within the field about the applicability of return periods as the main tool for generating inundation risk maps, versus scenario modelling of different hurricane categories. For some policy makers, it is generally more natural to talk about the impacts from hurricanes of different categories, rather than a seemingly abstract statistical value for a return period. The category approach allows for the development of strategies towards early warning protocols as well as evacuation and short-term disaster impact mitigation. The return period approach provides a firm statistical basis to measure and value risk exposure, and thus is important for long-term planning. Both approaches should then be considered as integral to the disaster risk management process.

With storm surge hazard areas clearly and systematically identified, appropriate disaster risk management plans can be put in place. Assuming that sufficiently detailed mapping has been obtained, it will be possible to identify the most vulnerable infrastructure, as well as to estimate the number of people that will be threatened by flooding. Armed with this knowledge beforehand, it will then be possible (given advance warning of hurricane track and intensity) to develop a strategy for the rapid evacuation of people in areas that are identified as being most vulnerable to storm surge inundation. Potential damage to critical roads and other coastal infrastructure may also be determined so that appropriate protective or mitigation measures may be employed.

4.6.2 Town planning

Planners and decision-makers are faced with the choice of which return period to use for planning. While common practice has been to use the 50-year event for the structural design of coastal protection within the region, this is not applicable for looking at long-term policies to reduce risk to storm surge inundation. Greater return periods, such as the 1 in 150 year, as a minimum, may be more appropriate given that

Considerations	Method 1	Method 2	Method 3
Near-shore conditions (complexity of seabed conditions, presence of reefs etc.)	Applicable for open shorelines. Not applicable for bays and harbours with complex bathymetry	Applicable to all near-shore formations	Applicable to all near-shore formations
Shoreline characteristics (position relative to predominant wave conditions, embayment etc.)	Not applicable for shoreline sheltered from predominant incident waves	Applicable to all shoreline characteristics	Applicable to all shoreline characteristics
Computational time and/or budget	Comparatively shorter computational time	Comparatively longer than method 1	Comparatively the longest but depends on the number of synthetic storms modelled
Early warning systems and evacuation plans	Not applicable	Applicable but considers only past occurrences	Most applicable as it allows inclusion of hypothetical storms
Policy and regulatory guidelines for long-term planning	Not recommended for long-term planning	Applicable, but consideration should be given to potential GSLR	Relevant for long-term planning

Table 2. Applicability of the three methods presented

recent hurricanes such as Ivan (2004) produced conditions statistically worse than the 1-in-150-year event. The hybrid approach offers the opportunity to analyse the differences between plans for the various return periods and further attempts to link them to a particular category of hurricane event.

As new developments are being proposed for previously uninhabited parts of the shoreline, appropriate setback limits and floor elevations can also be recommended.

4.6.3 Early warning systems and evacuation planning
Real-time forecasting of storm tracks is becoming a well-developed technique. Existing models used by the US National Hurricane Center and other such organisations provide reasonable predictions of storms' tracks. This allows for evacuation plans in the form of short-term adaptation based on projected 1- to 2-day tracks. These adaptation strategies need to be a part of the overall long-term master plan for evacuation and disaster management.

A long-term master plan should utilise the hindcast methods presented or similar approaches to develop the various possibilities of storm track and intensity; far in advance of any storm approaching. The method used needs to include hypothetical storm tracks and intensities and should be simplified for planning purposes as maximum envelopes of water level (MEOW). In these applications inundation maps are better developed according to various storm categories rather than return periods. MEOW maps should be prepared for each category of storm and possible related tracks.

4.6.4 Inundation mapping
In order to enhance the presentation of storm surge data and to facilitate its use by regulatory agencies, planning departments and engineering offices, it is important that the hazard data be presented in a consistent and clear manner. There follows a few guidelines for the data that should be contained in such mapping.

(*a*) First, a base map should be prepared on which all generated data can be superimposed. This base map is typically obtained through the use of geo-referenced images and maps. Depending on the scale of mapping used, at a minimum, data pertaining to infrastructure location (coastal structures, roadways etc.), critical facilities and social services, evacuation routes, shelters, public buildings, river and drainage courses, environmental resources and so on should be included.

(*b*) The base map should contain topographic information, which may be in the form of land contours or spot elevations, or both.

(*c*) Within the region, the requirements of appropriate mapping for storm surge delineation on a community level should be at a minimum scale of 1 in 10 000, with contour intervals of at least 1·0 m for the first 10 m in elevation above mean sea level.

5. Recommendations and commentary

5.1 Recommendations
The two main components in the scope of disaster management are disaster mitigation and disaster preparedness. Mitigation

involves both structural and non-structural measures to improve resilience for coastal communities. Preparedness involves forecasting damage, warning dissemination and evacuation planning. In the context of these two components, the framework for developing guidelines for regional storm surge mapping may be built on the following recommendations.

5.1.1 Preparedness: warning and evacuation plans

- Synthetic storms should be generated from the population of existing storm tracks for areas of interest (Cat 1 to Cat 5) using method 3 or a similar approach.
- Storm surge maps must be developed on a community scale to allow for proper determination of evacuation routes and shelter locations.

5.1.2 Mitigation: private sector development

- A 50- to 100-year event applying method 1 or 2 (or similar), based on the complexity of the site and scope of the development.
- Mapping needs to be done at a site-specific scale.

5.1.3 Mitigation: land use and social vulnerability reduction

- Low-frequency events are to be adopted for planning (at least 150-year events).
- Method 3 or similar approach should be used to incorporate the possible effects of climate change.
- Mapping needs to be done at a 'town' scale that would guide recommendations for zoning.

Further, the framework for developing guidelines for regional storm surge mapping in the context of improved coastal zone management may be built on the following recommendations:

5.1.4 Environmental regulations and coastal zone management

- Storm surge impacts need to be coupled with long-term beach erosion and reef degradation to revise setback limits.
- A paradigm shift is needed in the approach to protecting the coastline and infrastructure from storm surge. Coastal 'defence' needs to be incorporated with coastal 'enhancement', namely dune reconstruction, beach nourishment as opposed to just sea walls and revetments.

5.2 Commentary

Although several storm surge hazard mapping projects have been undertaken in the Caribbean, much more work remains to be done. Often the sponsored projects are in response to a hurricane disaster with focus on recently impacted areas. As such, areas which may be vulnerable but have not been recently impacted tend to be ignored, frequently for budgetary and political reasons. For example, several studies have been carried out for towns and communities along the south coast of Jamaica since the devastating impacts of Ivan (2004) and Dean (2007) which damaged these areas. Yet vulnerable towns on the North Coast such as Annotto Bay, Buff Bay and Port Maria, which have not been recently impacted, have not yet been studied.

Furthermore, as models and methods of storm surge predictions improve, hazard maps need to be updated and revised for areas that might have been mapped more than 10 years ago. These issues bring to the fore the relevance of storm surge mapping and the complications involved therein.

There is an urgent need for the development of a set of guidelines for the Caribbean. Such guidelines should be developed to encourage some level of regional consistency in the evaluation of storm surge and the development of inundation maps for the various coastal towns and communities. With the region at serious risk to impacts of climate change, particularly hurricane activity, a set of guidelines that direct evacuation strategies, disaster risk reduction policies and planning regulations is of utmost importance.

It is felt that if the budget allows, the combination of method 2 and method 3 is considered the preferred approach. This will allow for a wide range of applications as well as high accuracy. GSLR predictions should be included in the combination method to increase its reliability. This combination method will also consider changes in hurricane frequency and intensity which may be imminent climate change impacts.

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